H-alpha Observations using Closure Phases at the NPOI

G. Charmaine Gilbreath[a], Thomas A. Pauls[a], J. Thomas Armstrong[a],
David Mozurkewich[b], James H. Clark[a], Robert B. Hindsley[a], and Donald J. Hutter[c]
[a]U. S. Naval Research Laboratory, Code 7215, Washington, D. C. 20375,
http://code7215.nrl.navy.mil
[b]Seabrook Engineering, Lanham, MD 20706
[c]U. S. Naval Observatory, Flagstaff, AZ, 86002

ABSTRACT

We have enhanced the spectral resolution of the Navy Prototype Optical Interferometer (NPOI) at the H-alpha line to 3 nm (FWHM). We use customized filters that suppresses light in the ~600-725 nm window except for light at the H-alpha wavelength (656.3 nm). The bands shortward of 600 nm and longward of 725 nm are used for fringe tracking and for calibrating the system fringe visibility. We have used these filters to observe H-alpha emission from circumstellar material around Be stars. Closure phases from our initial observations of the Be star zeta Tau with three array elements suggest that the H-alpha emission is not centered on the star. We will show these three-element results, as well as recently-acquired data from the NPOI using 4, 5, and 6 stations.

Key Words: Optical Interferometry, interferometric imaging, Be Stars, H-alpha, NPOI

1. INTRODUCTION

The study of Be stars has been of interest for many years. Two topics of particular interest are the spatial extent and temporal variability of the H-alpha emission at 656.3 nm. In the last decade, this emission has been observed with the Mark III and GI2T interferometers [1-3] and with the NPOI in its initial three-siderostat configuration [4]. With the advent of six-beam observations with the NPOI, improved U-V plane coverage and imaging fidelity are within reach. The addition of custom narrow-band filters has made it possible to isolate the Hα line from the nearby stellar continuum, improving the imaging performance[5]. In this paper, we report on progress in observing such sources using the multi-beam capability at the NPOI and these special filters.

2. EXPERIMENTAL CONFIGURATION

The Navy Prototype Optical Interferometer is located near Flagstaff, Arizona. The array is reconfigurable array and when complete, will provide observations at visual wavelengths using six array elements simultaneously, with baselines up to 437 meters long [6]. A recent photo of the NPOI is shown in Figure 1. The NPOI is collaboration between the U.S. Naval Research Laboratory and the U.S. Naval Observatory, in cooperation with the Lowell Observatory.

We have carried out a number of observations using up to six siderostats (up to eleven baselines) in 16 spectral channels, both with and without customized Hα filters. During the night, the observer could quickly reconfigure the array to use from three to six siderostats, depending on the declination and hour angle of the source, the quality of the seeing, and the signal-to-noise ratio. Over the past 16 months, a number of Be sources with their calibrators were observed. These included the Be stars Kappa Draconis and Zeta Tauri.

The custom filters were designed to pass a narrow band of emission on either side of the Hα line (656.3 nm). The filters also had to reject both the nearby stellar continuum and scattered HeNe laser metrology light

New Frontiers in Stellar Interferometry, edited by Wesley A. Traub,
Proceedings of SPIE Vol. 5491 (SPIE, Bellingham, WA, 2004)
0277-786X/04/$15 · doi: 10.1117/12.555221

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2004**	2. REPORT TYPE	3. DATES COVERED **00-00-2004 to 00-00-2004**

4. TITLE AND SUBTITLE **H-alpha Observations using Closure Phases at the NPOI**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Code 7215,4555 Overlook Avenue SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We have enhanced the spectral resolution of the Navy Prototype Optical Interferometer (NPOI) at the H-alpha line to 3 nm (FWHM). We use customized filters that suppresses light in the ~600-725 nm window except for light at the H-alpha wavelength (656.3 nm). The bands shortward of 600 nm and longward of 725 nm are used for fringe tracking and for calibrating the system fringe visibility. We have used these filters to observe H-alpha emission from circumstellar material around Be stars. Closure phases from our initial observations of the Be star zeta Tau with three array elements suggest that the H-alpha emission is not centered on the star. We will show these three-element results, as well as recently-acquired data from the NPOI using 4, 5, and 6 stations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Figure 1. Photograph of the Navy Prototype Optical Interferometer near Flagstaff, Arizona, is shown. Six siderostats were recently brought on line to enable up to 15 beam combinations using 16 to 32 spectral channels.

(632 nm), as well as pass stellar continuum light further out from the Hα line. This band-pass design allows us to isolate the Hα line from the stellar continuum that would enter in the same spectral channel, but pass the continuum further from the line to enable fringe tracking.

Characteristics of the filters are shown in Figure 2. Transmission through 16 spectroscopic channels are also shown as well as placement on the beam combining table at the NPOI in Figure 3.

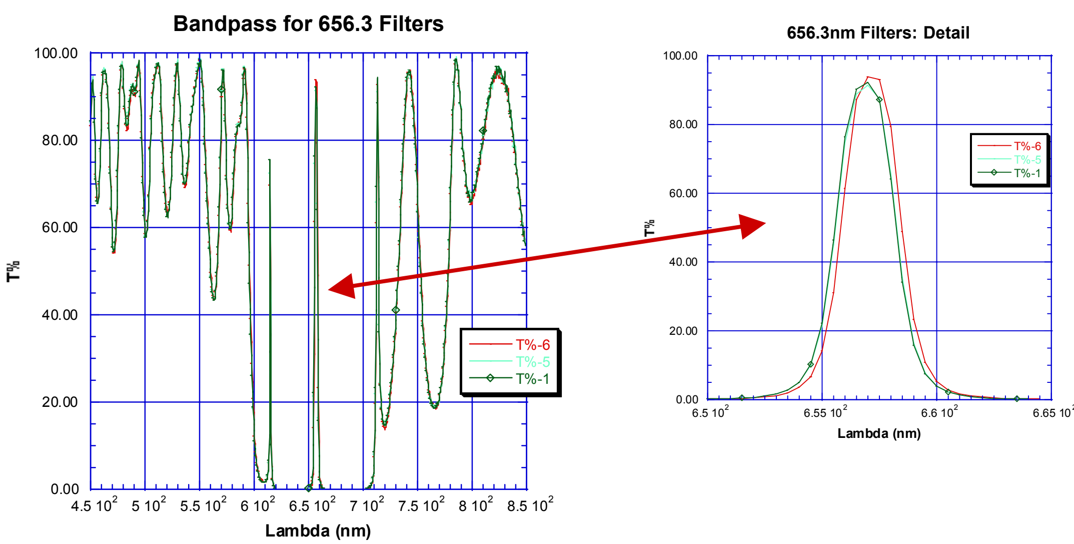
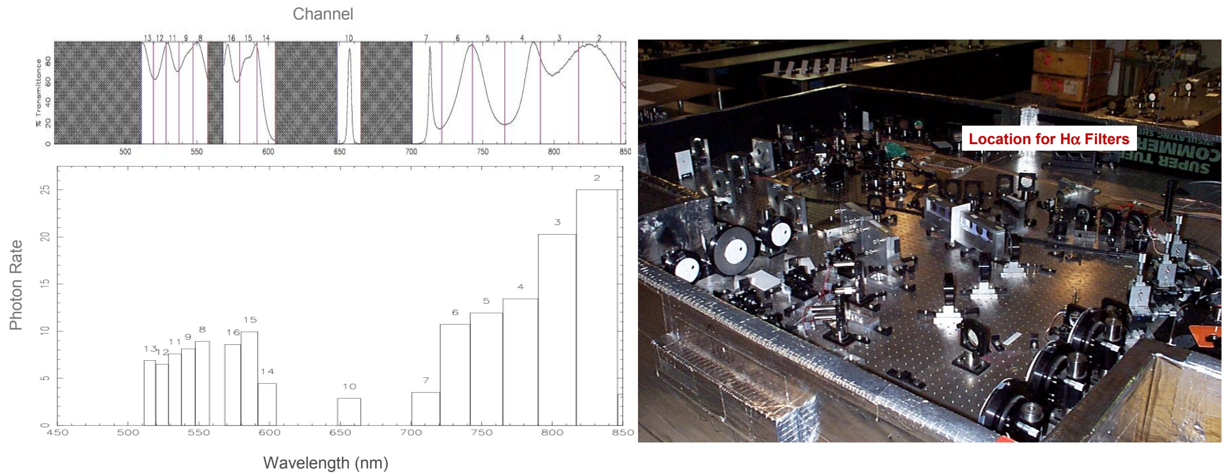


Figure 2. Shown are the spectral characteristics of custom filters designed to pass Hα (656.3 nm), suppress the light in the adjacent channels as well as that from the NPOI metrology beam of 632 nm, and let pass as much light as possible in the adjacent bands to enable simultaneous fringe tracking.

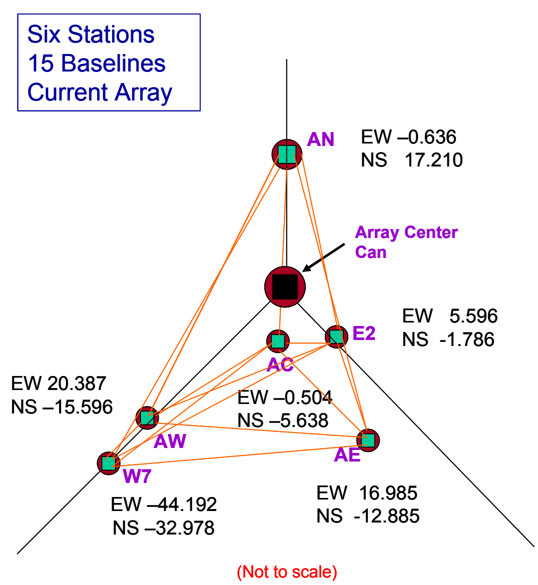
The array configurations used in these campaigns included all of the astrometric stations, East-2 and West-7. Figure 4 shows the locations and baselines for these stations. On nights where six-station data was obtained, baselines sampling the UV plane were from 7m to 64 m.



(a) **(b)**

Figure 3. Custom filters and their placement on the NPOI beam combiner table are shown: (a) Channel assignments and filter throughput with measured photon rate; (b) Location of filters on the beam combining table.

We observed with these configurations from November, 2002, through April, 2004. Table I is a listing of dates and array configurations. Seeing conditions and number of scans are recorded as well as comments made by the observers at the site. The comments were useful in understanding the instrument's response on a given night. Most of this data has been reduced. A sample set is shown in this paper.



Index	Location	Distance (m)
1	AW – AE	37.470
2	W7 – AE	64.392
3	CA – AE	18.931
4	E2 – AE	15.903
5	AN – AE	34.874
6	AN – E2	19.992
7	AC – E2	7.214
8	AW – E2	29.425
9	W7 – E2	58.752
10	AC – AN	22.848
11	AW – AN	38.293
12	W7 – AN	66.453
13	AW – AC	22.237
14	W7 – AC	51.538
15	W7 – AW	29.476

Figure 4. NPOI siderostat locations considered for the current array with all spectrographs operational. Baseline lengths are shown in adjacent table.

Table 1. Observing Campaigns for H-alpha Studies at NPOI

Date	Seeing	#Scans	Configurations	Comments
11/19/2002	b0-b2	81	ac(2)-ae(3)-aw(4)-an(6)	
11/20/2004	b1-b2	86	ac(2)-ae(3)-aw(4)-an(6)	
11/21/2002	b3	87	ac(2)-ae(3)-aw(4)-an(6)	
11/22/2002	b4-b5	102	ac(2)-ae(3)-aw(4)-an(6)	Zeta Tau
11/23/2002	b0-b2	60	e2(1)-ac(2)-ae(3)-aw(4)-an(6)	
11/24/2002	b0-b3	103	e2(1)-ac(2)-ae(3)-aw(4)-an(6)	
11/25/2002	b0-b2	34	e2(1)-ac(2)-ae(3)-aw(4)-an(6)	
11/27/2002	b0	85	e2(1)-ac(2)-ae(3)-aw(4)-an(6)	
11/28/2002	b1-b2	60	e2(1)-ac(2)-ae(3)-aw(4)-an(6)	
12/3/2003	b0 to b4	61	e2(1)-ac(2)-ae(3)-aw(4)-w7(5)-an(6)	Intermittent fringe tracking problems
12/4/2003	b1 to b4	54	e2(1)-ac(2)-ae(3)-aw(4)-w7(5)-an(6)	FDL problems; fiducial loss
12/5/2003	b1/b2	65	e2(1)-ac(2)-ae(3)-aw(4)-w7(5)-an(6)	Trouble fringe tracking, very little data with full array
12/7/2003	b0/b1	25	ac(2)-ae(3)-aw(4)-w7(5)-an(6)	clouds; poor seeing
12/11/2003	b1/b2	74	ac(2)-ae(3)-aw(4)-w7(5)-an(6)	Some tracking problems; clouds; 1 h Tau scan
12/13/2003	b0	42	ac(2)-ae(3)-aw(4)-w7(5)-an(6)	poor fringe track all night
12/14/2003	b2	23	ac(2)-ae(3)-aw(4)-w7(5)-an(6)	no fringes on AE-AW
12/17/2003	b3	73	e2(1)-ac(2)-ae(3)-aw(4)-w7(5)-an(6)	6 Station Data!!
12/18/2003	b3	92	Need this one	No problems - 6-way!
12/19/2003	b4	39	ae(3)-aw(4)-an(6)	FDL problems; some 4-way
12/20/2003	b2	2	Need this one	cloudy; FDL3 got stuck once
12/21/2003	b2 to b0	20	ae(3)-aw(4)-w7(5)-an(6)	cloudy; closed at midnight
12/29/2003	b3.5	54	ae(3)-aw(4)-w7(5)-an(6)	seeing degraded after 0900 UT
12/29/2003	b3.5	54	ae(3)-aw(4)-w7(5)-an(6)	seeing degraded after 0900 UT
1/5/2004	b3-b4	56	ae(3)-aw(4)-w7(5)-an(6)	
1/6/2004		17	ae(3)-aw(4)-w7(5)-an(6)	poor seeing; clouds; AN could not find stars
1/7/2004	b1	5	ae(3)-aw(4)-w7(5)-an(6)	cloudy
1/9/2004	b2	100	ae(3)-aw(4)-an(6)	large FDL jitter at times
1/10/2004	b3/b4	196	ae(3)-aw(4)-an(6)	!!! *****
1/11/2004	b4/b5	225	ae(3)-aw(4)-an(6)	!!! *****
1/12/2004	b5/b5+	32	ae(3)-aw(4)-an(6)	Only clear for 1 hour; can't read data (timing)
1/13/2004	b4	43	ae(3)-aw(4)-an(6)-W7(5)	not all baselines
2/28/2004				Engineering run - recenter
3/1/2004	b3	81		
3/7/2004	b3	167	e2(1)-ac(2)-ae(3)-aw(4)-an(6)	
3/8/2004	b3	42	e2(1)-ac(2)-ae(3)-aw(4)-an(6)	
3/9/2004	b1-b2	64	e2(1)-ac(2)-ae(3)-aw(4)-w7(5)-an(6)	
3/26/2004	b1 to b0	39	need	poor seeing were not sent the min. for 3/26
3/27/2004	b0 to b2	55	ac(2)-ae(3)-aw(4)-w7(5)-an(6)	poor seeing
3/28/2004	b0/b1	80	ac(2)-ae(3)-aw(4)-w7(5)-an(6)	
3/29/2004	b1 to b0	93	ac(2)-ae(3)-aw(4)-w7(5)-an(6)	some clouds; poor seeing - reduced
3/30/2004	b3	108	ac(2)-ae(3)-aw(4)-w7(5)-an(6)	best yet
3/31/2004	b2/b1	106	ac(2)-ae(3)-aw(4)-w7(5)-an(6)	

3. SOME RESULTS

We present some results from the campaigns listed in the table. These samples reflect 6, 5, 4, and 3 station observing. Continuum results were compared with single line results to assess the existance and magnitude of possible emission within the resolution of the instrument and filters.

3.1 Zeta Tauri

Zeta Tauri is one of the brightest Be stars and has been observed with several optical interferometers in the past [3]. The NPOI observations are the first to allow closure phase measurements in the Hα line and in the adjacent continuum. If the Hα emission is symmetrically distributed around the central star, the closure phase will be zero inside and outside the line. However, if there is an asymmetry in the line-emitting region, the closure phase will be non-zero at the wavelength of the line. Figure 5 shows a closure phase measurement made on 24 November 2002, using the triangle AE-AC-AN, which shows a non-zero closure phase at the position of the Hα line. The figure also shows the closure phase measurement made on 7 March 2004 using the triangle AE-AC-

AN that also has a non-zero closure phase in the line. Grouped, the three sets of figures show the squared visibilities on baselines AE-AC, AN-AC, and AE-AN, respectively. These observations are the first closure phase measurements that suggest an asymmetric line-emitting region around Zeta Tau. Observations by Vakili et al. [2] using the GI2T also suggest that the emitting region is offset from the central star.

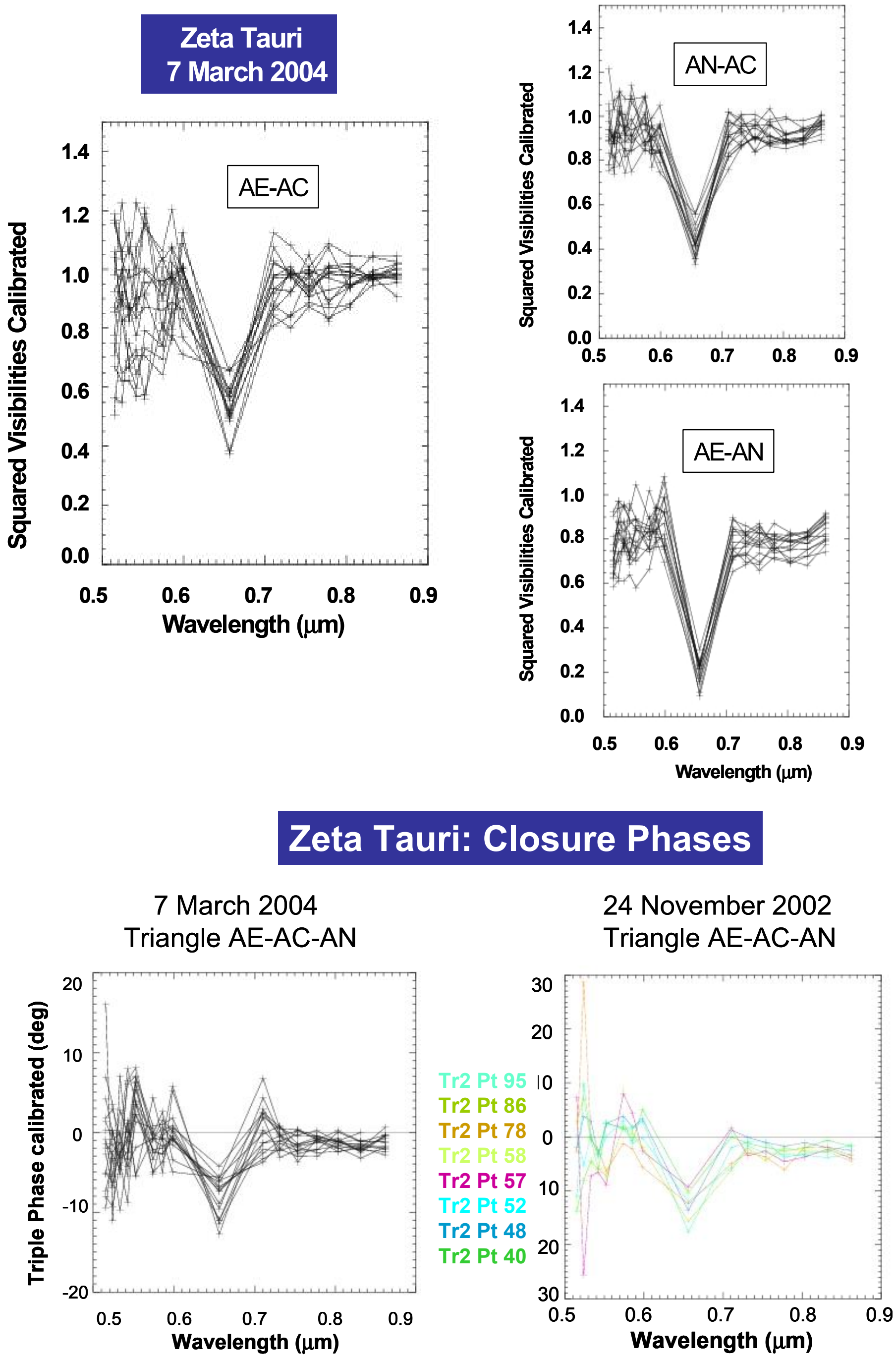
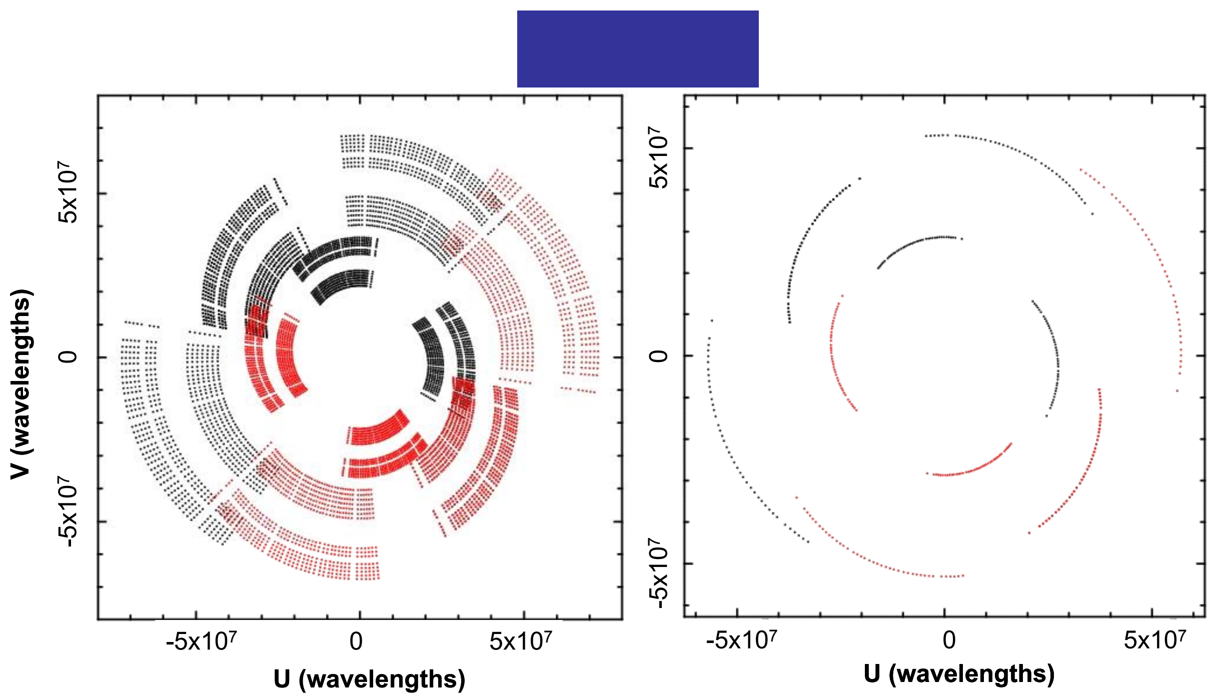


Figure 5. Closure phase measurements made on Zeta Tauri using the NPOI are shown above. These results span 15 months and show a non-zero closure phase at 656.3 nm.

3.2 Kappa Draconis

Observations of Kappa Draconis were made to assess the imaging capabilities of the NPOI. Simultaneous observations were made with 4 stations giving 6 baselines and 3 closure phases. The data were calibrated with standard NPOI software and converted to a UVFITS file that was loaded into the AIPS++ imaging software package. The data has 16 spectral channels, 15 in the continuum and a single channel in the Hα line. AIPS++ allows the user to select the spectral channels to be imaged. Figure 6 shows the UV coverage for the continuum channels, where dots represent individual spectral channels and the arcs are a series of measurements on a given baseline. These data were imaged using CLEAN and self-calibration in AIPS++. The result is shown in Figure 7. The yellow patch in the figure is the restoring beam: 2.4 x 2.0 milliarcseconds. The central source, the Be star itself, is unresolved and appears to mimic the beam. Figure 11 shows the UV coverage for the single Hα spectral line channel. The arcs represent a series of observations throughout the night on 6 baselines. Even with the drastic reduction in UV coverage, the restored image shown above, is quite good. The image again mimics the restoring beam (2.5 x 2.2 milliarcseconds), which means that the Hα emission comes from a region that is smaller than about 2.4 milliarcseconds.



(a) (b)

Figure 6. UV Coverage is shown for Kappa Draconis from March 30, 2004. (a) UV for Continuum; (b) UV for H-alpha line (656.3).

4. CONCLUSIONS

In a series of observations spanning 16 months, we have detected apparent Hα emission from a number of stellar objects. Baselines up to 38 meters enabled a restoring beam on the order of 2.4 x 2.0 mas. Customized filters were used which pass the 656.3 nm energy, suppress close adjacent channels, and let light from either side pass to enable fringe tracking. The technique is proven to be a successful for the detection of specific line emission using the NPOI. By using 6,5,4, and 3 station beam combining, we were able to image stellar bodies without *a priori* modelling.

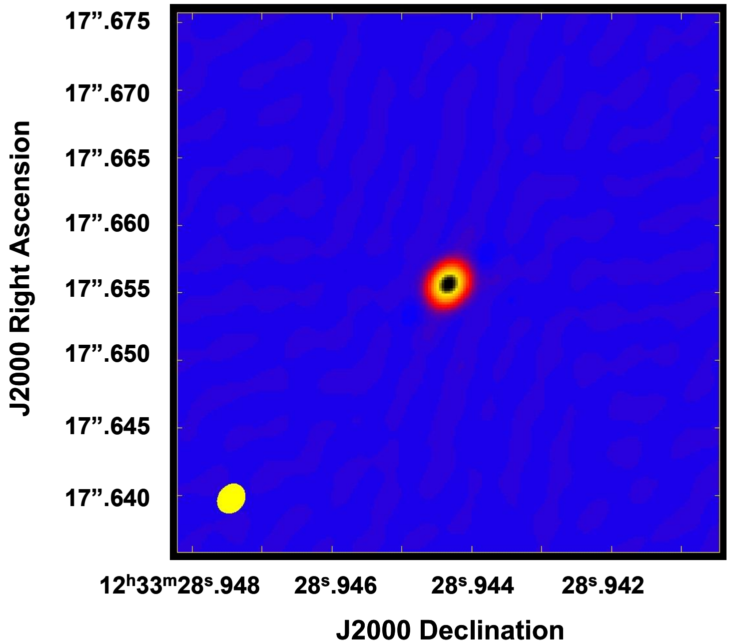
Some scientific results include indications that Zeta Tauri has Hα emission, due to the measured non-zero closure phase in at least two sets of data taken over a year apart. Other observing campaigns have resulted in measurements that indicate that Be emission from Kappa Draconis must come from a region smaller than 2.4 mas.

ACKNOWLEDGMENTS

The authors would like to acknowledge the NPOI observers who worked tirelessly to obtain data in these campaigns. We would also like to thank the Oceanographer of the Navy and the Office of Naval Research for support.

REFERENCES

1. Quirrenbach, et. al., *Astroph. J.* 479, 477-496 (1997).
2. F. Vakili, et.al., *Astron. Astroph.* 335, 261-265 (1998).
3. Tycner et al. and references therein, Astronomical Journal, 127, 1194 (2004).
4. T. A. Pauls, et.al., *Bull. Am. Astron. Soc.* 198, 51.16 (2001).
5. G. Charmaine Gilbreath, et.al., Proceedings of the SPIE, 4838, 573-583 (2003).
6. J. T. Armstrong, et.al., *Astroph. J.* 496, 550-571 (1998).



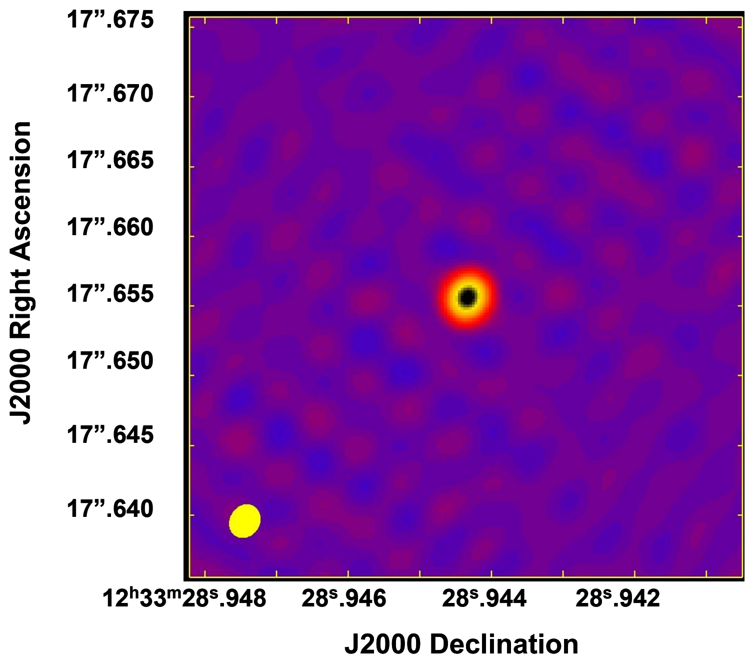


Figure 7. Images of Kappa Draconis from March 30 data. (a) Continuum; (b) H-alpha emission. Yellow ellipse is the point spread function of the array. Results shown that the H alpha emission emits from a region smaller than 2.4 milliarcseconds.